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PREDICTING HEIGHT FOR UNDAMAGED AND DAMAGED TREES IN SOUTHWEST OREGON

by

ML Hanus

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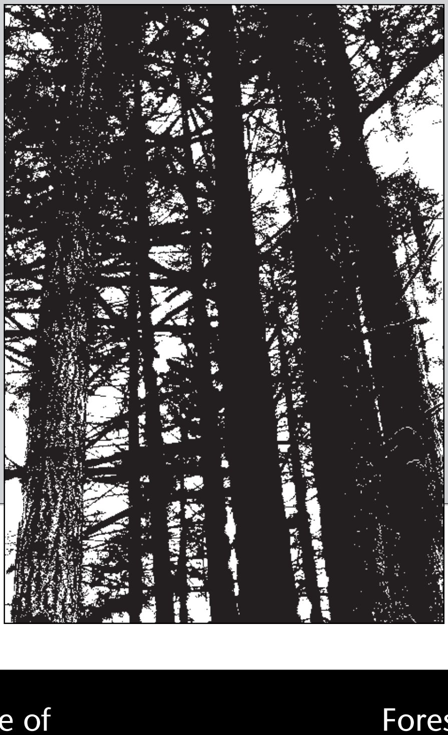
DD Marshall



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Abstract

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Equations for predicting tree height as a function of diameter outside bark at breast height are presented for various tree species common to southwest Oregon. Data for damaged and undamaged trees were analyzed with weighted nonlinear regression techniques. The effects of specific damaging agents and their severity on the height-diameter relationship were explored. Damage correction multipliers were estimated, then used to correct predicted height where damage was noted. Because the relationship between height and diameter changes with the competitive position of the tree in a stand, alternative equations are presented that include the average height and diameter of the 40 largest-diameter undamaged conifer trees per acre. Foresters can use these "height-diameter" equations to reduce the time-consuming task of measuring heights of every tree in an inventory, stand exam, or timber cruise. They can also use these equations to estimate the change in height as diameter changes. These equations will be incorporated into the new southwest Oregon version of ORGANON, which extends the model to older stands and stands with a heavier component of hardwood species.

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Introduction

The total height of a tree (Ht) is useful in assessing tree volume (Walters et al. 1985; Walters and Hann 1986) and stand productivity through site index (Hann and Scrivani 1987), but is time-consuming to measure accurately. Foresters have often chosen instead to sample some trees and estimate the heights of the unsampled trees with equations. Traditionally, these equations have included only tree diameter at breast height (DBH) as an independent variable (Curtis 1967). However, other competitive position variables, such as the average DBH and Ht of the 40 largest-diameter undamaged conifer trees per acre (D40 and H40, respectively), may improve estimates for trees growing in even-aged stand structures (Krumland and Wensel 1988; Hanus et al. 1999).

Foresters can use these equations to estimate height growth by applying them to a sequence of diameters either measured directly in a continuing inventory or predicted indirectly from a diameter growth equation. The latter approach can be valuable for modeling growth and yield of trees and stands.

The objective of this study was to develop equations for predicting Ht as a function of DBH, by itself or in conjunction with D40 and H40, for various tree species commonly found in southwest Oregon:

Conifers

Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Grand fir	*Abies grandis* (Dougl. ex D. Don) Lindl.
Incense-cedar	*Libocedrus decurrens* Torr.
Pacific yew	*Taxus brevifolia* Nutt.
Ponderosa pine	*Pinus ponderosa* Dougl. ex Laws.
Sugar pine	*Pinus lambertiana* Dougl.
Western hemlock	*Tsuga heterophylla* (Rafn.) Sarg.
White fir	*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.

Hardwoods

Bigleaf maple	*Acer macrophyllum* Pursh
California black oak	*Quercus kelloggii* Newb.
Canyon live oak	*Quercus chrysolepis* Liebm.
Cherry	*Prunus* spp.
Golden chinkapin	*Castanopsis chrysophylla* (Dougl.) A. DC.
Oregon white oak	*Quercus garryana* Dougl. ex Hook.
Pacific dogwood	*Cornus nuttallii* Aud.
Pacific madrone	*Arbutus menziesii* Pursh
Tanoak	*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.
Willow	*Salix* spp.

Data Description

Data for this analysis came from two studies associated with the development of the ORGANON growth model (Hann et al. 1997). The first set of data was collected in 1981, 1982, and 1983, as part of the southwest Oregon Forestry Intensified Research (FIR) Growth and Yield project. This study included 391 plots in an area extending from near the California border (42°10′N) in the south to Cow Creek (43°00′N) in the north, and from the Cascade crest (122°15′W) on the east side to approximately 15 mi west of Glendale (123°50′W). Elevations ranged from 900 to 5,100 ft. Selection was limited to stands under 120 years old and 80% basal area (BA) in conifer. The second study (1992–1996) covered about the same area, but also included stands with trees over 250 years old and younger stands with a greater component of hardwoods. An additional 138 plots were measured in this study.

In either study, each stand had 4 to 10 sample points. At each point trees were sampled with a nested plot design that selected trees ≤4.0 in. DBH on a 1/229-acre fixed-area plot, trees 4.1 to 8.0 in. on a 1/57-acre plot, or trees >8.0 in. with a 20 basal area factor (BAF) variable plot. In the more recent study, trees >36.0 in. were selected with a 60 BAF prism. Ht was measured to the nearest 0.1 ft on all trees, either directly with a 25- to 45-ft telescoping fiberglass pole or, for taller trees, indirectly with the pole-tangent method (Larsen et al. 1987). Trees with broken or dead tops were measured to the top of the live crown.

Measuring the height of leaning trees depended on the severity of the lean, with all measurements taken at right angles to the direction of the lean. If the degree of lean was ≤15°, Ht was measured directly to the leaning tip (i.e., the lean was ignored). If the degree of lean was >15°, the tree tip was visualized in a vertical position and Ht measured to that imaginary point. DBH was measured to the last whole 0.1 in. with a diameter tape for all trees taller than 4.5 ft. These measurements were then used to calculate D40 and H40 of Douglas-fir, grand fir, ponderosa pine, sugar pine, and white fir growing in even-aged stands. Trees classified as emergent were excluded from the calculation of D40 and H40.

The type and severity of any damage was also noted for each sample tree. Descriptions of the methods and codes for denoting damage are in the appendix. The equations developed by Larsen and Hann (1987) for southwestern Oregon had excluded trees with height damage. We created one data set that contained all trees except those with height damage (damage codes 72, 73, and 75 through 79). A description of this data set is in Table 1. Preliminary analysis of the current data set indicated that other types of damage significantly affected the Ht-DBH relationship. Therefore, two data sets were added—one that contained only undamaged trees (Table 2), and another containing top-damaged trees (Table 3). Finally, a fourth data set was created for undamaged trees in even-aged stands (Table 4).

Table 1. Diameters and heights of undamaged and damaged trees (excluding top damage; codes 72, 73, and 75 through 79).

		DBH (in.)		Height (ft)	
Species	# trees	mean	range	mean	range
Conifers					
Douglas-fir	17,541	15.0	0.1–84.0	82.2	4.6–274.8
Grand/White firs	3,170	12.9	0.1–53.2	73.6	4.6–202.1
Incense-cedar	1,842	9.5	0.1–90.0	38.8	4.6–183.7
Pacific yew	50	5.6	0.1–22.6	17.6	4.8–45.0
Ponderosa pine	1,297	14.9	0.1–54.6	77.6	4.6–221.8
Sugar pine	426	19.6	0.2–69.7	85.0	4.9–175.5
Western hemlock	164	9.6	0.1–30.8	54.1	4.7–155.8
Hardwoods					
Bigleaf maple	75	6.8	0.1–28.5	43.9	4.9–96.4
California black oak	334	11.5	0.1–49.0	44.7	4.7–120.9
Canyon live oak	276	3.0	0.1–22.6	17.8	4.7–57.9
Cherry/Pacific dogwood	287	0.9	0.1–6.8	11.4	4.6–43.0
Golden chinkapin	1,021	3.9	0.1–28.0	23.2	4.6–89.2
Oregon white oak	38	7.6	0.5–24.5	33.7	5.5–72.2
Pacific madrone	1,466	8.0	0.1–44.7	41.9	4.6–105.1
Tanoak	566	2.6	0.1–36.8	17.9	4.6–108.2
Willow	334	1.2	0.1–9.6	15.4	5.0–41.9

Table 2. Diameters and heights of undamaged trees only.

		DBH (in.)		Height (ft)	
Species	# trees	mean	range	mean	range
Conifers					
Douglas-fir	11,745	15.4	0.1–81.3	87.3	4.6–274.8
Grand/White firs	1,865	13.5	0.1–44.8	80.1	4.6–200.9
Incense-cedar	1,026	9.6	0.1–68.8	40.9	4.6–183.7
Pacific yew	25	3.1	0.2–11.5	14.4	4.8–32.2
Ponderosa pine	888	15.7	0.2–54.6	82.7	4.9–189.7
Sugar pine	218	19.8	0.2–53.3	89.8	5.6–171.8
Western hemlock	81	10.2	0.1–23.6	59.3	4.8–125.0
Hardwoods					
Bigleaf maple	43	6.6	0.2–20.3	45.3	5.2–96.4
California black oak	224	11.2	0.1–49.0	44.1	4.8–120.9
Canyon live oak	205	2.9	0.1–15.2	17.2	4.7–57.9
Cherry/Pacific dogwood	200	0.9	0.1–6.8	11.4	4.6–43.0
Golden chinkapin	610	4.5	0.1–24.0	26.3	4.6–89.2
Oregon white oak	27	7.5	1.9–20.1	37.0	12.0–72.2
Pacific madrone	1,013	7.5	0.1–34.6	41.4	4.6–99.7
Tanoak	317	2.6	0.1–21.2	18.0	4.6–100.7
Willow	228	1.1	0.2–3.8	14.6	5.0–41.9

Table 3. Diameters and heights of trees with top damage (codes 72, 73, and 75 through 79).

		DBH (in.)		Height (ft)	
Species	# trees	mean	range	mean	range
Conifers					
Douglas-fir	2,877	15.9	0.1–78.2	79.5	4.6–241.7
Grand/White firs	543	14.1	0.1–46.4	74.0	4.9–195.0
Incense-cedar	257	11.1	0.1–53.6	41.8	4.6–160.2
Pacific yew	28	6.0	0.1–16.9	19.8	4.8–44.0
Ponderosa pine	524	16.3	0.3–59.8	78.2	6.4–203.1
Sugar pine	83	21.8	0.2–62.2	88.6	5.0–177.5
Western hemlock	28	8.1	0.1–20.0	41.0	4.6–79.2
Hardwoods					
Bigleaf maple	56	6.8	0.3–21.8	43.1	8.3–100.1
California black oak	215	10.4	0.1–34.0	40.4	4.8–118.2
Canyon live oak	317	2.2	0.1–9.1	14.6	4.7–40.4
Cherry/Pacific dogwood	115	1.6	0.1–6.9	14.8	4.8–40.0
Golden chinkapin	336	2.9	0.1–27.6	16.4	4.7–77.4
Oregon white oak	15	2.9	0.2–7.6	18.9	5.5–37.7
Pacific madrone	937	9.5	0.1–42.1	45.6	4.7–107.5
Tanoak	327	2.0	0.1–17.3	14.9	4.6–61.0
Willow	67	1.4	0.1–4.7	17.2	5.0–42.5

Table 4. Diameters and heights, including D40 and H40, of undamaged trees from even-aged stands.

		DBH (in.)		Height (ft)	
Species	# trees	mean	range	mean	range
Douglas-fir	8,064	14.4	0.1–73.4	85.5	4.6–229.3
Grand/White firs	1,159	14.1	0.1–42.7	85.5	4.6–181.4
Ponderosa/ Sugar pines	604	15.0	0.3–53.0	79.8	4.9–176.7
		D40 (in.)		**H40 (ft)**	
Species	# plots	mean	range	mean	range
Douglas-fir	356	17.4	1.8–43.4	91.8	11.4–208.7
Grand/White firs	156	18.0	3.7–43.4	95.8	20.9–208.7
Ponderosa/ Sugar pines	121	16.2	4.2–33.9	84.3	17.7–165.9

Data Analysis for Undamaged Trees Only

Many of the published height-diameter equations use a log-linear model form both to simplify parameter estimation and to correct for heterogeneous variance (Curtis 1967; Wykoff et al. 1982). The residuals of these log-linear equations, however, are not normally distributed (Larsen and Hann 1987), which makes correcting for log bias difficult (Flewelling and Pienaar 1981). Therefore, we chose the following nonlinear equation form to characterize the particular relationship of *Ht* to *DBH*:

$$Ht = 4.5 + \exp\left(\alpha_0 + \alpha_1 DBH^{\alpha_2}\right) \qquad [1]$$

where α_0, α_1, and α_2 are regression coefficients. Equation [1] was fit separately to each species in the undamaged data set (Table 2) using weighted nonlinear regression and the weight of 1.0/DBH, as previously done by Larsen and Hann (1987), Wang and Hann (1988), and Hanus et al. (1999).

Hanus et al. (1999) determined that the following form, which includes transformations of D40 and H40, explained more of the variation for even-aged stands of Douglas-fir or western hemlock growing in the coastal regions of the Pacific Northwest:

$$Ht = 4.5 + (H40 - 4.5) \times \left[\exp\left(\beta_0 \times DBH^{(\beta_1 + \beta_2(H40 - 4.5))}\right) / \exp\left(\beta_0 \times D40^{(\beta_1 + \beta_2(H40 - 4.5))}\right)\right] \qquad [2]$$

where β_0, β_1, and β_2 are regression coefficients to be estimated by nonlinear regression.

Undamaged Douglas-fir, white and grand firs combined, and ponderosa and sugar pines combined had sufficient data from even-aged stands to estimate the parameters for Eq. [2] (Table 4). This equation was fit separately to these species groups using weighted nonlinear regression (weight of 1.0/DBH). The height-diameter relationship of grand fir and white fir were not found to be statistically different from each other, so the data sets were combined as was done by Larsen and Hann (1987). The data sets for ponderosa pine and sugar pine were combined for the same reason.

Results for Undamaged Trees Only

Tables 5 and 6 contain the regression coefficients and their standard errors for Eq. [1] (fit to undamaged trees) and Eq. [2] (fit to undamaged trees growing in even-aged stands). There were not enough trees to fully characterize the height-diameter relationship for western hemlock in Eq. [1]; therefore, the α_0 value was set according to Larsen and Hann (1987). The weighted mean square error (MSE) and coefficients of determination ($\bar{R}^2$) are also included in each table.

Table 5. Regression coefficients (standard error) and associated weighted mean square error (MSE) and adjusted coefficient of determination ($\bar{R}^2$) for undamaged tree fits of Eq. [1].

Species	α_0	α_1	α_2	MSE	$\bar{R}^2$
Conifers					
Douglas-fir	7.133682298	-5.433744897	-0.266398088	12.8083	0.7005
	(0.0642855)	(0.04845780)	(0.00597117)		
Grand/White firs	6.75286569	-5.52614439	-0.33012156	12.4637	0.7550
	(0.1440452)	(0.08959619)	(0.01858820)		
Incense-cedar	10.04621768	-8.72915115	-0.14040106	6.0013	0.8241
	(0.6549889)	(0.6260772)	(0.0143007)		
Pacific yew	5.10707208	-3.28638769	-0.24016101	1.2002	0.8378
	(1.2308074)	(1.3317683)	(0.095921)		
Ponderosa pine	6.27233557	-5.57306985	-0.40384171	17.0286	0.5350
	(0.210485)	(0.0949953)	(0.0422428)		
Sugar pine	5.81876360	-5.31082668	-0.47349388	10.9485	0.5293
	(0.2602093)	(0.2569061)	(0.0800153)		
Western hemlock	6.58804*	-5.25312496	-0.31895401	12.4148	0.7301
		(0.18941638)	(0.01521942)		
Hardwoods					
Bigleaf maple	5.20018445	-2.86671078	-0.4225522	27.5975	0.5369
	(0.6015805)	(0.61405573)	(0.14780511)		
California black oak	5.04832439	-3.32715915	-0.43456034	11.9933	0.4852
	(0.2100750)	(0.16432523)	(0.061675628)		
Canyon live oak	9.01612971	-7.34813829	-0.134025626	5.2815	0.8222
	(2.6253048)	(2.63902880)	(0.052647298)		
Cherry/Pacific dogwood	7.49095931	-5.40872209	-0.16874962	3.4242	0.6825
	(1.5823995)	(1.59418712)	(0.0482735)		
Golden chinkapin	9.2251518	-7.65310387	-0.15480725	8.3575	0.7383
	(1.1553477)	(1.1427771)	(0.02866387)		
Oregon White oak	4.11895138	-5.33052764	-1.22472614	12.5372	0.3567
	(0.2494183)	(2.11964021)	(0.4642986)		
Pacific madrone	6.53558288	-4.69059053	-0.24934807	11.1044	0.5651
	(0.3574122)	(0.34342754)	(0.0272922)		
Tanoak	8.49655416	-6.68904033	-0.16105112	5.2366	0.8109
	(0.9817186)	(0.99185543)	(0.0273372)		
Willow	3.26840527	-0.95270859	-0.98015696	11.6597	0.4504
	(0.1764379)	(0.1935608)	(0.1666117)		

*Value from Larsen and Hann (1987).

Table 6. Regression coefficients (standard error) and associated weighted mean square error (MSE) and adjusted coefficient of determination ($\bar{R}^2$) for undamaged tree fits of Eq. [2].

Species	β_0	β_1	β_2	MSE	$\bar{R}^2$
Douglas-fir	-3.485635287 (0.02203705)	-0.255712209 (0.00997180)	-0.001555149 (0.000153796)	6.6897	0.7887
Grand/White firs	-4.376160718 (0.060086243)	-0.231693907 (0.02497961)	-0.001334070 (0.000309475)	8.4531	0.7670
Ponderosa/ sugar pines	-4.047994965 (0.11776753)	-0.135864020 (0.05456248)	-0.005647510 (0.000758789)	6.4882	0.8029

Examination of the weighted $\bar{R}^2$ values for both equations indicated that Eq. [2] explained more of the variation in height than did Eq. [1]. When Eq. [1] was fit to the even-aged Douglas-fir data set used to fit Eq. [2], the resulting weighted $\bar{R}^2$ was only 0.5350, indicating that Eq. [2] was a substantial improvement over Eq. [1] for even-aged stands. However, Eq. [2] is restricted to even-aged stands only, and its use requires the measurement of H40 and D40. Therefore, the remainder of the analysis was conducted with Eq. [1].

Data Analysis for Undamaged and Damaged Trees

The impact of damage on predicted height was characterized in three analyses. First, Eq. [1] was fit to the data set containing both undamaged and damaged trees, but excluding height damage codes 72, 73, and 75 through 79 (Table 1), using weighted nonlinear regression (weight of 1.0/DBH). This analysis paralleled that of Larsen and Hann (1987).

Second, Eq. [1] was fit to all damaged trees for each species using weighted nonlinear regression (weight of 1.0/DBH). Any differences in the magnitude of impact on height that might occur among damaging agents or by level of severity were ignored.

The third analysis explored whether the magnitude of impact of damage varied by the type and severity of a damaging agent. For each tree species, multiplicative correction factors (CF) to total tree height for a particular damage type and severity were calculated as follows:

1. The regional height-diameter prediction equation (i.e., Eq. [1] with parameters from Table 5) was calibrated to each plot to reduce variation caused by between-plot differences in the height-diameter relationship. Each plot's undamaged tree heights were regressed on predicted tree heights using the regression model

$$CPHt = c_{1,i}\left(PHt - 4.5\right) \qquad [3]$$

where $CPHt$ = predicted height above breast height calibrated to the ith plot's undamaged trees for a species, and PHt = predicted height for undamaged trees from the ith plot, from Eq. [1] and parameters from Table 5. Parameter c_1 was estimated by using weighted linear regression through the origin (weight of 1.0/DBH), then tested for significant difference from 1.0 with a t-test ($p = 0.10$). Values of c_1 judged not significant were set to 1.0 (i.e., the regional equation was used for the plot).

2. The multiplicative CF for a given damaging agent and its severity was calculated across all plots containing the damaging agent by regressing the damaged tree heights on both the *CPHt* from Step 1 and the severity of damage:

$$DPHt - 4.5 = d_1\, CPHt + d_2 I_s CPHt \qquad [4]$$

where *DPHt* = predicted height above breast height for trees damaged by a particular agent, and where I_s = zero if damage was light, or $I_s = 1.0$ if damage was severe.

If neither parameter was significant, then no correction was reported for that damaging agent. If both parameters were significant, then d_1 was reported as the CF for light damage and $d_1 + d_2$ was reported as the CF for severe damage. If the parameter d_1 was significant and the parameter d_2 was not significant, then d_1 was reestimated by the following equation:

$$DPHt - 4.5 = d_1 CPHt \qquad [5]$$

fit to the combined light and severe data using weighted linear regression. The resulting value of d_1 was reported as the CF for both levels of severity. If the parameter d_1 was not significant and the parameter d_2 was significant, then the CF for light damage was set to 1.0 and d_2 was reestimated by the following equation:

$$DPHt - 4.5 = d_2 CPHt \qquad [6]$$

fit to just the severe data using weighted linear regression. The resulting value of d_2 was reported as the CF for the severe level of damage.

Given the CF for a particular type of damage and its severity, the resulting Ht can be predicted by

$$DPHt = 4.5 + CF(PHt - 4.5) \qquad [7]$$

Results for Undamaged and Damaged Trees

Tables 7 and 8 contain regression coefficients, their standard errors and weighted MSE, and $\bar{R}^2$ for Eq. [1], fit to both undamaged and damaged trees (excluding damage codes 72, 73, and 75 through 79), and to damaged trees only (including damage codes 72, 73, and 75 through 79). There were insufficient trees to fully characterize the height-diameter relationship for western hemlock in Eq. [1]; therefore the a_0 parameter was set to the value from Larsen and Hann (1987).

Table 7. Regression coefficients (standard error) and associated weighted mean square error (MSE) and adjusted coefficient of determination ($\bar{R}^2$) for the undamaged and damaged tree fits of Eq. [1].

Species	α_0	α_1	α_2	MSE	$\bar{R}^2$
Conifers					
Douglas-fir	7.153156143	-5.36900835	-0.25832512	13.4742	0.7483
	(0.04719341)	(0.03805181)	(0.00412773)		
Grand/White firs	6.638003799	-5.44399465	-0.33929196	13.5354	0.7761
	(0.10051703)	(0.06450052)	(0.01359464)		
Incense-cedar	8.776627288	-7.4383668	-0.16906224	6.0011	0.8321
	(0.29145219)	(0.27375587)	(0.00958049)		
Pacific yew	6.402691396	-4.79802411	-0.16317997	3.3923	0.5259
	(2.1157064)	(2.18753699)	(0.07935097)		
Ponderosa pine	7.181264435	-5.90709219	-0.27533719	18.8883	0.5678
	(0.31151450)	(0.21521413)	(0.02877925)		
Sugar pine	6.345116767	-5.30026188	-0.35264183	10.5163	0.6896
	(0.225786)	(0.12516630)	(0.03720471)		
Western hemlock	6.58804*	-5.35325461	-0.31897786	13.6446	0.6801
		(0.13911176)	(0.01126417)		
Hardwoods					
Bigleaf maple	5.02002617	-2.51228202	-0.42256497	33.7005	0.4723
	(0.43119683)	(0.46196626)	(0.11458968)		
California black oak	4.907340242	-3.18017969	-0.46654227	14.757	0.4001
	(0.17401201)	(0.13299227)	(0.06115592)		
Canyon live oak	7.762149257	-6.04759773	-0.16308399	5.4621	0.6349
	(1.41789223)	(1.42791437)	(0.0431032)		
Cherry/Pacific dogwood	5.252315215	-3.13509983	-0.26979750	5.3267	0.5707
	(0.6720079)	(0.68429392)	(0.05460133)		
Golden chinkapin	9.21600278	-7.63409138	-0.15346440	7.9199	0.7455
	(0.86870057)	(0.86423704)	(0.02102084)		
Oregon white oak	4.112227912	-3.81483387	-0.97310812	12.7155	0.3640
	(0.28951211)	(0.96390473)	(0.38409599)		
Pacific madrone	5.42457261	-3.56317104	-0.36177689	12.8983	0.5112
	(0.14621428)	(0.13676209)	(0.02514774)		
Tanoak	7.398142262	-5.5099273	-0.19080702	5.7511	0.7856
	(0.48074635)	(0.48819964)	(0.01971783)		
Willow	3.862132151	-1.5294776	-0.62476287	9.7758	0.4903
	(0.20977385)	(0.22176819)	(0.08716379)		

*Value from Larsen and Hann (1987).

Table 8. Regression coefficients (standard error) and associated weighted mean square error (MSE) and adjusted coefficient of determination ($\bar{R}^2$) for the damaged tree fits of Eq. [1]. Includes trees with damage codes 72, 73, and 75 through 79 from Table 3.

Species	α_0	α_1	α_2	MSE	$\bar{R}^2$
Conifers					
Douglas-fir	7.252043542	-5.401808725	-0.240614082	15.7398	0.7344
	(0.07282031)	(0.06248145)	(0.00557526)		
Grand/White firs	7.175183187	-5.875971296	-0.276310625	15.3153	0.7573
	(0.19811993)	(0.15379039)	(0.017434504)		
Incense-cedar	8.631372074	-7.238223885	-0.168212468	6.4528	0.8180
	(0.36673565)	(0.34665664)	(0.01230631)		
Ponderosa pine	8.85868802	-7.155908433	-0.167045337	20.9503	0.4998
	(0.85865405)	(0.77946756)	(0.03004037)		
Sugar pine	6.761006811	-5.563150073	-0.294366925	11.2461	0.7067
	(0.35261101)	(0.24193420)	(0.03937362)		
Western hemlock	6.58804*	-5.301898319	-0.301122711	13.7847	0.6235
		(0.16575870)	(0.01408101)		
Hardwoods					
Bigleaf maple	4.764987654	-2.108576305	-0.419087275	29.9818	0.3458
	(0.40355548)	(0.46282389)	(0.11390421)		
California black oak	4.522782121	-3.065902316	-0.611125378	18.1227	0.2925
	(0.15537157)	(0.15504675)	(0.09719164)		
Canyon live oak	11.97007871	-10.17210818	-0.08100435	4.9837	0.4886
	(4.23837032)	(4.24888642)	(0.03523694)		
Cherry/ Pacific dogwood	4.802631034	-2.639566725	-0.312385445	8.5873	0.4692
	(0.58282107)	(0.60477217)	(0.07014394)		
Golden chinkapin	12.01865704	-10.42308774	-0.10111655	7.8594	0.6640
	(2.27591870)	(2.277548051)	(0.024579684)		
Oregon white oak	3.993518259	-2.434350060	-0.679335075	6.0995	0.5970
	(0.36294922)	(0.357638953)	(0.220848041)		
Pacific madrone	5.199350819	-3.269272753	-0.378925767	15.3222	0.3215
	(0.14421316)	(0.128069105)	(0.030836158)		
Tanoak	7.703103923	-5.733918634	-0.158288526	6.3301	0.6703
	(0.68436198)	(0.694499469)	(0.020904221)		
Willow	4.417605216	-2.002611485	-0.459855008	5.7561	0.6655
	(0.26403245)	(0.277161856)	(0.065654585)		

*Value from Larsen and Hann (1987).

Table 9 contains the multiplicative CF and their standard errors for Eq. [7] by specific damaging agents and their severity. Only those damaging agents with statistically significant parameter values are included.

Table 9. Damaged tree correction factor (CF) multipliers on predicted undamaged tree heights from Eq. [1] with parameters from Table 3, with standard errors (SE).

Species	Damage code*	# Trees	CF for light damage	SE for light damage	CF for severe damage	SE for severe damage
Conifers						
Douglas-fir	23	629	NA	NA	0.9452	0.0052
	24	273	NA	NA	0.9255	0.0088
	32	110	0.9331	0.0166	0.8668	0.0172
	43	67	0.9184	0.0268	0.9184	0.0268
	61	1,460	1.1148	0.0071	1.1148	0.0071
	71	1,331	0.9818	0.0044	0.9394	0.0150
	72	1,293	0.9460	0.0056	0.8224	0.0080
	73	748	0.9488	0.0059	0.8861	0.0110
Grand/White firs	24	194	NA	NA	0.9637	0.0114
	32	9	1.0000	NA	0.7273	0.0577
	71	38	1.0000	NA	0.8769	0.0265
	72	223	0.9091	0.0140	0.8057	0.0240
	73	39	1.0000	NA	0.8898	0.0229
	75	35	NA	NA	0.8343	0.0379
Incense-cedar	32	55	0.8439	0.0221	0.8439	0.0221
	61	335	1.0516	0.0138	1.0516	0.0138
	72	49	1.0000	NA	0.8027	0.0292
Ponderosa pine	42	23	0.8223	0.0230	0.8223	0.0230
	61	62	1.3789	0.0646	1.3789	0.0646
	72	51	1.0000	NA	0.7739	0.0269
	73	158	0.9171	0.0165	0.9171	0.0165
Sugar pine	21	50	NA	NA	0.8738	0.0235
	61	11	1.3090	0.0872	1.3090	0.0872
	72	45	0.8843	0.0268	0.8843	0.0268
Hardwoods						
California black oak	72	49	1.0000	NA	0.6646	0.0444
Canyon live oak	61	21	1.2360	0.0919	1.2360	0.0919
	75	255	NA	NA	1.1586	0.0214
Cherry/Pacific dogwood	61	26	1.3228	0.0646	1.7602	0.1183
Golden chinkapin	61	21	1.0000	NA	1.1705	0.0503
	72	46	0.7583	0.0407	0.7583	0.0407
Pacific madrone	32	37	1.0000	NA	0.7424	0.0315
	72	83	1.0000	NA	0.7617	0.0357
	73	100	0.9014	0.0205	0.9014	0.0205
	75	601	NA	NA	0.9638	0.0098
	76	42	NA	NA	0.8046	0.0313
	91	10	0.6620	0.0508	0.6620	0.0508
Tanoak	43	19	0.8037	0.0355	0.8037	0.0355
	61	81	1.1617	0.0392	1.1617	0.0392
	72	29	1.0000	NA	0.7598	0.0771
Willow	61	20	1.3376	0.0323	1.3376	0.0323

* Damage codes explained in appendix.

Discussion

Including D40 and H40 did increase the precision of predicting tree height for Douglas-fir, grand and white firs combined, and ponderosa and sugar pines, growing in even-aged stands. As Hanus et al. (1999) found, the improvement in $\bar{R}^2$ was substantial. However, the resulting $\bar{R}^2$ in this study are lower than those of Hanus et al. (1999). Their better fits to Douglas-fir may be attributed to their using a data set of trees from research-quality plots established in younger stands, whereas the trees in the current study were from operational stands with a much greater range of stand structure and age. On the research plots, the heights were subsampled from undamaged trees, concentrating on larger trees. The heights of all trees were measured in our study.

Damage was common (33%–64%) for trees in the data set presented in Tables 1, 2, and 3. Figure 1 shows heights for undamaged Douglas-fir predicted using Eq. [1] and Table 5 values compared to heights for undamaged and damaged trees (with and without damage codes 72, 73, and 75 through 79) predicted using Eq. [1] and the parameters from Tables 7 and 8. DBH values from 0 to 100 in. were plotted. Differences in predicted heights between the equation for undamaged trees and the equation for damaged trees ranged from 5.8% for a 20-in. tree to 6.8% for a 100-in. tree. Predictions from the equation for combined undamaged and damaged trees were closer to those from the equation for undamaged trees than to those from the equation for damaged trees because the data set included more undamaged trees than damaged ones.

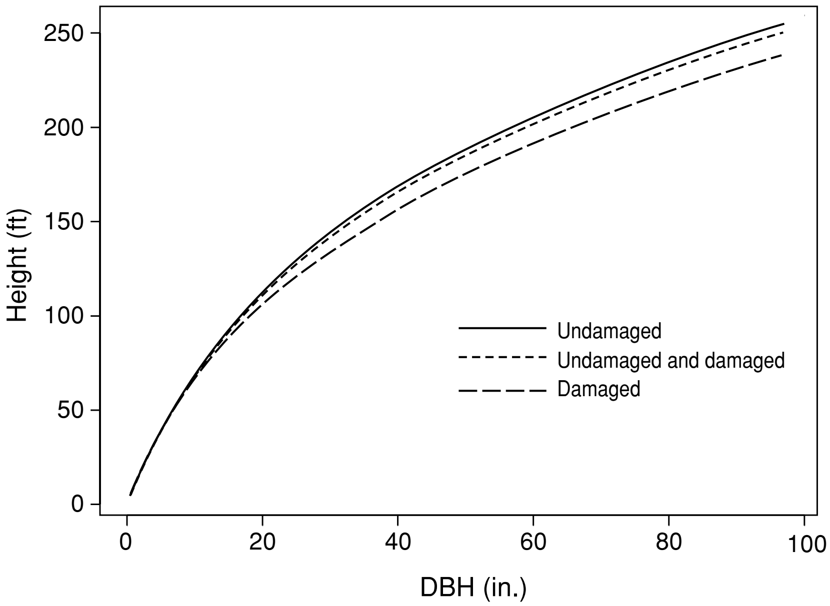

Figure 1. Heights of damaged and undamaged Douglas-fir, as predicted by Eq. [1]: $Ht = 4.5 + \exp\left(\alpha_0 + \alpha_1 DBH^{\alpha_2}\right)$ — — — *excludes trees with damage codes 72 and 73;* - - - - - - - *includes these top-damaged trees. Note: data for the two dashed lines overlap.*

An evaluation of specific damaging agents and their severity revealed that some agents affected tree height substantially more than others (Table 9). For example, two of the most frequent damage codes were suppression of small trees (damage code 61), and trees with missing, dead, or spiked tops (damage code 72). Small, suppressed trees were taller than undamaged trees of the same species and diameter, with multipliers ranging from 1.0516 to 1.7602. Trees with missing, dead, or spiked tops were shorter than undamaged trees of the same species and diameter, with multipliers ranging from 0.6646 to 0.9460. In both cases, significantly severe damage resulted in a greater deviation from the undamaged tree height.

These height-diameter equations provide new and useful information about tree species growing in the even- and uneven-aged, pure and mixed-species stands of southwest Oregon. To predict unmeasured heights, we recommend using Eq. [1] with damaged and undamaged tree parameters from Table 7 when data on damaging agents are not available. If specific damaging agents and their severity are noted, then Eq. [1] can be used with the undamaged tree parameters from Table 5 and the appropriate damage CF from Table 9. These multipliers could also be applied to the undamaged tree equations reported by Hanus et al. (1999). For predicting change in height, we recommend using Eq. [1] with the undamaged tree parameters from Table 5. These equations will be used in the new southwest Oregon version of ORGANON (Hann et al. 1997) to extend the model to older stands and stands with a heavier component of hardwood species.

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Appendix – Basis of Data Coding

Table A1. Damage codes

Damage	Code
No damaging agent	00
No damaging agent but tree is on a skid road	07
No damaging agent but tree is on an excavated skid road	08
No damaging agent but tree is near a skid road (both types)	09
Insects	
Bark beetles	11
Defoliators	12
Sucking insects	13
Bud- and shoot-deforming insects	14
Tree has insects and is on a skid road	17
Tree has insects and is on an excavated skid road	18
Tree has insects and is near a skid road (both types)	19
Disease	
White pine (and sugar pine) blister rust (always severe)	21
Other rust cankers on main bole	22
Conks on bole, limb, or ground near tree (always severe)	23
Mistletoe (always severe)	24
Other diseases and rot	25
Tree has disease and is on a skid road	27
Tree has disease and is on an excavated skid road	28
Tree has disease and is near a skid road (both types)	29
Fire Damage	
Scorched crown	31
Fire scar on bole	32
Tree has fire damage and is on a skid road	37
Tree has fire damage and is on an excavated skid road	38
Tree has fire damage and is near a skid road (both types)	39
Animal Damage	
Domestic	41
Porcupine	42
Other wildlife	43
Tree has animal damage and is on a skid road	47
Tree has animal damage and is on an excavated skid road	48
Tree has animal damage and is near a skid road (both types)	49
Weather Damage	
Lightning	51
Wind	52
Other	53
Tree has weather damage and is on a skid road	57
Tree has weather damage and is on an excavated skid road	58
Tree has weather damage and is near a skid road (both types)	59

Suppression Damage

Suppressed seedlings or saplings $\leq$ 6 in. DBH	61
Suppressed pole or sawtimber size tree > 6 in. DBH	62
Tree is suppressed and is on a skid road	67
Tree is suppressed and is on an excavated skid road	68
Tree is suppressed and is near a skid road (both types)	69

Other Damage

Natural mechanical injury	71
Top out or dead (spike top)	72
Forked top or multiple stem	73
Needles or leaves noticeably short, sparse, or off-color	74
Excessive lean—over 15° from vertical (always severe)	75
Excessive forking—a hardwood tree that forks within the first 8 ft, or a conifer that forks within the first 12 ft, with the main fork then forking again within 8 or 12 ft, respectively (always severe)	76
Tree has other damage and is on a skid road	77
Tree has other damage and is on an excavated skid road	78
Tree has other damage and is near a skid road (both types)	79

Logging and Construction Damage

Damage by powered equipment	81
Other logging damage	82
Tree has logging damage and is on a skid road	87
Tree has logging damage and is on an excavated skid road	88
Tree has logging damage and is near a skid road (both types)	89
Excessive taper or deformity—will not produce a 12-ft conifer or 8-ft hardwood log	91
Off-site tree	92
Tree has excessive taper and is on a skid road	97
Tree has excessive taper and is on an excavated skid road	98
Tree has excessive taper and is near a skid road (both types)	99

Table A2. Guide for rating severity of damage

Disease Damage

White Pine Blister Rust. This disease attacks all Northwest five-needled pines: white, whitebark, sugar, and limber pines. Record this item as severe when any evidence of the disease is found. Symptoms in infested trees may include discolored bark, the outer edges of the discolorations yellowish to orange; shallow blisters on the bark that may exude a sticky substance or masses of yellow aeciospores; characteristic spindle- or diamond-shaped swelling of the stem or branches accompanied by scaly lesions and black pycnial scars; or copious resin exudation from ruptured bark in areas of infection.

Other rust cankers of the main bole. Record as severe only when cankers deform the bole, cause open wounds, or threaten to girdle the tree. Lodgepole pine is often infected with *Peridermium harknessii* "hip" cankers, which sometimes kill the tree.

Conk on bole or limb or ground near base of tree. Code as severe whenever any conks are observed.

Mistletoe. This is coded as severe damage.

Other diseases and rot. In immature trees, record as severe any disease that appears to threaten the tree's survival to maturity or would reduce its quality at maturity because of topkilling, deformity, or decay of bole or serious reduction of tree vigor. In mature trees, record infections that would seriously jeopardize survival over the next 10 years.

Examples of other disease and rot are: Pole Blight of white pine; needle blights, wilts, and rusts; dry rot associated with sunscalds and mechanical damage; needle cast; scabs and leaf galls; and diebacks.

Fire Damage

Crown Scorch. In cases where only the foliage has been killed by fire, record fire damage as light unless the fire-killed foliage reaches into the upper one-third of the crown. Ground fires may kill foliage on lower branches without seriously damaging the tree.

Basal Scar. In recording fire damage, classify basal scars as light damage unless they have killed the cambium on at least half the bole circumference.

Animal Damage

Record animal damage as severe for trees when at least half the bole circumference has been girdled, or when browsing has so seriously harmed seedlings or saplings that they will probably not develop into sound trees.

Weather Damage

Record as severe when weather damage would prevent immature trees from surviving to maturity or prevent mature trees from surviving 10 years, e.g., loss of 70% of the crown to wind or snowbreak, shattering of the bole by lightning, or partial uprooting by wind.

Suppression Damage

Live, suppressed seedlings or saplings. Suppressed understory trees are common in old-growth stands, but may occur in second-growth timber or even as residual trees after logging. Suppressed seedlings or saplings are usually characterized by extremely short or nonexistent internodes; twisted, gnarled stems; short, flat crowns of live needles forming “umbrella-shaped” trees; or extremely sparse foliage. Such damage should be coded as severe. When in question cut down a sapling that is *off the point* and count the rings to determine its age. Code as light those seedlings that would probably respond to release.

Other Damage

Natural mechanical injury. Code as severe such things as damage to bole that would reduce the quality of the product at maturity in immature trees or prevent mature trees from living 10 more years. Examples are broken limbs in the crown caused by other trees falling into them, or a bole girdled by at least half by mechanical actions such as rubbing in the wind or boulders rolling against a bole.

Top out or dead (spike top). Code as severe for immature trees. Code as light for mature trees unless more than 10 ft of the top is dead or broken out.

Forked-out or multiple stem. Code as light for small double leaders in tall trees but code as severe all major forks or multiple stems in immature trees. *Do not code as severe for mature trees*.

Needles or leaves noticeably short, sparse, or off-color. Code as light any minor chlorosis or general “redbelting” of trees caused by frost conditions (when the needle tips of trees in a large area are tinged).

Excessive lean >15° from vertical. Record as severe for all trees, regardless of age or size.

Sound cull-forked tree. Code as severe for a hardwood tree that forks within the first 8-ft log or a conifer that forks within the first 12-ft log, the main fork of which forks again within 8 or 12 ft, respectively.

Table A3. Guide for rating severity of insect damage

Insect/Host	Light damage	Severe damage
Bark beetles Douglas-fir	Small amount of clear or white pitch on bole.	*Current Damage*. Needles turning yellow or red over most of the tree (tree is dying). Clear or white pitch on bole. Boring dust in bark crevices is conspicuous.
Bark beetles pines (ponderosa, jeffrey, lodgepole, sugar, western white)	Copious pitching: pitch tubes large and consist of yellowish to clear masses of pitch. No live insects under bark.	Needles turning yellow to red over most of the tree. Small red pitch tubes (less than 0.25 in. in diameter) common. Reddish boring dust in bark flakes and crevices, or around base of tree. Live insects under bark.
Ips beetles ponderosa and sugar pines	In a tree beyond conventional rotation age, the top few feet of crown is fading or dead.	Tops killed in seedlings or saplings, or in poletimber and sawtimber trees below rotation age. (In some cases, especially in dense stands of saplings, ips beetles may kill every tree in a small area.)
Defoliators Dominant, co-dominant, and intermediate crown classes		
All species except hemlock and grand fir	Entire crown less than 50% defoliated. Top 10 ft of crown less than 75% defoliated or discolored. Leader normal, but perhaps short. Current foliage with less than 50% of tips discolored or less than 50% of needles missing. A few branches with no shoot growth.	Entire crown more than 50% defoliated. Top 10 ft of crown more than 75% defoliated or discolored. Leader deformed or killed. Current foliage with more than 50% of tips discolored or more than 50% of needles missing. Many branches with no new shoot growth.
Hemlock and grand fir		All defoliation damage is severe.
Balsam woolly aphid All crown classes of subalpine, Pacific silver, and grand firs		Any degree of balsam woolly aphid infestation on true firs is severe.
Sitka spruce weevil Sitka spruce. Usually attacks trees 8–60 ft tall. Leaders that are currently weeviled begin to droop in August (often turn brown).	Old weevil attacks, causing slight deformity of main stem.	Current weevil infestation with drooping leader; one or more side branches assuming dominance. Mere presence of attack on trees > 20 ft tall reflects significant growth loss. Old damage that has resulted in serious crooks or deformities, if weevil-caused.

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